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Analysis of flow stability boundaries of ERVC system

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ABSTRACT

ERVC is widely adopted as a part of in-vessel retention (IVR) in severe accident management strategies. In this paper，two-phase flow instability in natural circulation loops of external reactor vessel cooling (ERVC) system in a large size power PWR (CAP 1700 with a thermal power 5000 MWt) is simulated and evaluated by the RELAP5 code. Under certain conditions, flow instability of ERVC system are obtained. It is a kind of density wave oscillation that occurs in non-equilibrium boiling in the heat section and void flashing in the riser at low equilibrium quality and low system pressure. The calculation results show such oscillation course clearly. And several parameters affecting the flow stability are discussed.

Keywords: flow instability, two phase flow natural circulation, subcooled boiling, external reactor vessel cooling (ERVC).

INTRODUCTION

External reactor vessel cooling (ERVC) is an effective part of in-vessel retention (IVR). Natural circulation cooling is a key issue in the design of ERVC system. In ERVC system, flow is induced by density difference between the riser and the downcomer resulting from a large volumetric change when the fluid occurs phase changes (see Fig. 1). Under some operational conditions (pressure, inlet and outlet resistance coefficient, heating power, etc) the natural circulation flow instability may arise in the system. The flow instability can cause problems to system operation, control and may reduce the thermal margin of the system. Therefore the conditions are studied under which the system is stable.

Extensive studies were performed to deal with two-phase flow instabilities. The two-phase flow instabilities at low pressure of ERVC system have rarely studied. Although the natural circulation flow characteristics were observed to be very unstable in the heating experiment which

had been performed to evaluate the feasibility of ex-vessel cooling, the mechanism of the instability was not investigated. Among varied instability types occurred in the natural circulation loop the density-wave instability is the typical dynamic instability. Fukuda and Kobori [1] have classified the density-wave instability as two main different types of instabilities, the so-called Type-I and Type-II instabilities. At low pressures, the Type-I instability becomes more pronounced as a result of the so-called flashing phenomenon [2] which results in a suddenly vapor generation due to the decrease in hydrostatic head along the flow path. And instabilities have been observed in experimental facilities [2][3][4]. But the phenomena involved appear to be complex and have not been fully clarified, therefore the characteristics and mechanism of the flashing-induced instability are needed for a better understanding.

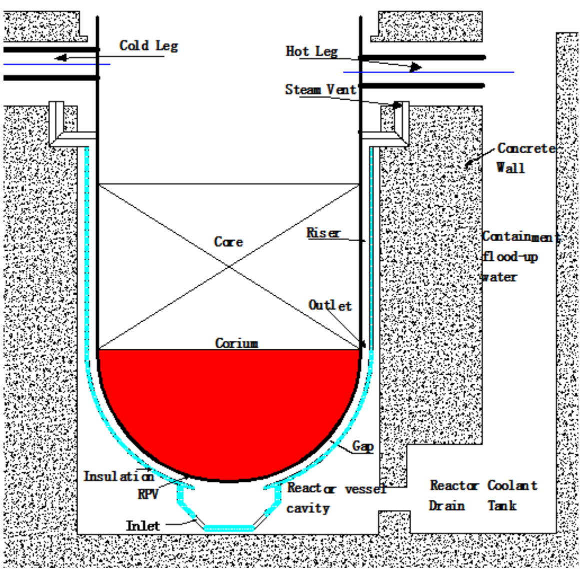


Fig.1 Schematic diagram of the external reactor vessel cooling in CAP1700

This paper addresses the modeling of flashing-induced instabilities using RELAP5 code. The mechanism of flashing-induced instability has been examined in detail. Stability boundaries have been measured as a function of power and inlet temperature at different system pressures.

RELAP5 CODE MODELING

RELAP5 (Reactor Excursion and Leak Analysis Program) is an advanced, best-estimate, reactor thermal-hydraulic simulation code, developed at Idaho National Engineering and Environmental Laboratory (INEEL). The RELAP5 hydrodynamic model is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture that can contain non-condensable components in the steam phase and/or a soluble component in the water phase. The RELAP5/MOD3.4 version of the code was used in the test simulation. Kozmenkova and Rohde[5] reported the ability of RELAP5 to simulate flashing induced instabilities in the natural circulation low-pressure systems.

Fig.2 shows the RELAP5 nodalization of the system. Pipe 100 represents the vertical access tunnel. Valve 151 is the water inlet assembles located at the bottom of thermal insulation. The flow path at the lower head is divided into 8 parts along the radial direction, which are simulated by component 200—207, and to consider the existence of crossflow in the flow path, multiple junction 211 is used. There are 22 nodes, which have different inclination angles from 0° to 90°, in component 20X (X=0, 1, …, 7). Component 30X (X=0, 1, …, 7) represents the adiabatic vertical riser, and then they gather together in the component Branch 701. After going through Pipe 840, steam will vent to time dependent volume(TDV) 530 through air dome 900, which represents the containment, and the water will flow back to the vertical access. TDV 805 represents the system for feed-water. In the figure, the red part is heat structure, where heat transfer happens. Heat structure 20X (X=0,1, …, 7) represents input heat at the lower head. The water from inlet assembles is heated and two-phase mixture is generated. In the steady calculation, heat structure 610 is used to ensure

the inlet water temperature constant.

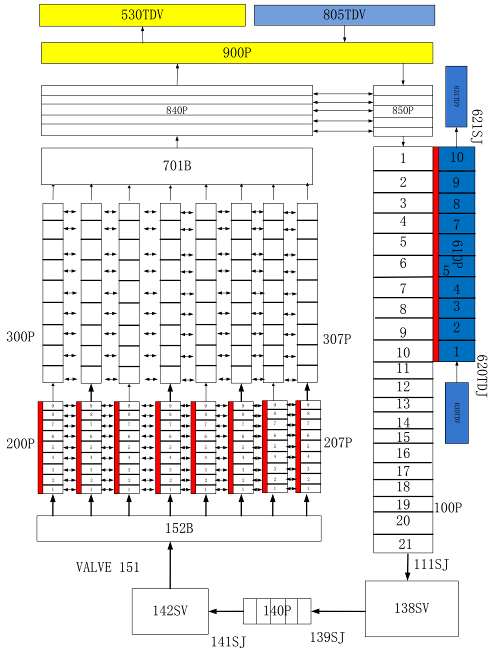


Fig.2 The system nodalization

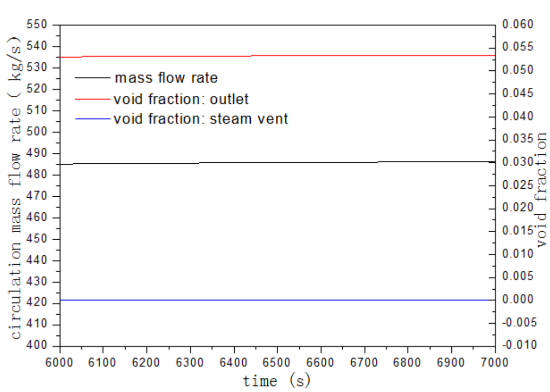
And the heat flux along the surface of the vessel lower plenum was calculated from the heat flux distribution as a function of the angular position using mini-ACOPO correlation[6].

INSTABILITY CHARACTERISTICS

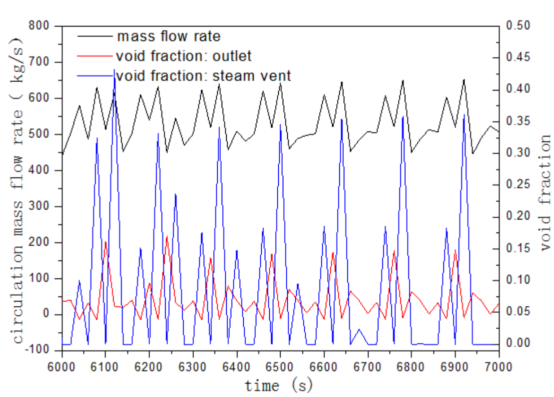
A series of calculations was carried out to study the characteristics of flashing-induced flow instabilities of ERVC system. The results were performed at pressures of 1 bar, 2.5 bar and 4 bar and for different structures of the adiabatic vertical riser. During each case the power level and the temperature at the inlet of the heated section were kept constant. And then the flow instabilities will occur if the heated power increases step by step. Although the power increment is very small, it can cause the instabilities in the ERVC system. The flow oscillation periods generally range between 50s and 100s, the frequencies are high. Flow oscillation amplitude can reach up to 95% of the mean magnitude of mass flow rate.

3.1. Representative waveforms and instability phenomenology

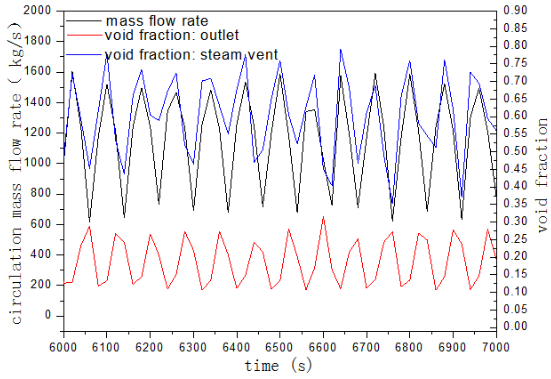
Fig. 3 (a)-(d) shows representative waveforms when system pressure is set to be 2.5 bar, power is 40MW and K_{in} is 2.15. Each graph shows the natural circulation mass flow rate transients which was obtained at a different inlet subcooling: (a) stable single-phase circulation at higher subcooling, (b) intermittent natural circulation, (c) unstable two-phase circulation, (d) stable two-phase circulation at low inlet subcooling. At single-phase circulation the liquid temperature remains below saturation. Void fractions of 0.0% and 5.3% are generated in the steam vent and outlet, respectively, and remain constant. As soon as the inlet temperature increases, steam bubbles are generated in the heated section (subcooled boiling) below the riser inlet and flashing in the riser is triggered. The intermittent natural circulation occurs as soon as the system passes from single-phase to two-phase operation. Finally, stable two-phase circulation takes place; in this case a much higher flow rate is achieved with respect to single-phase natural circulation due to the considerable density difference.



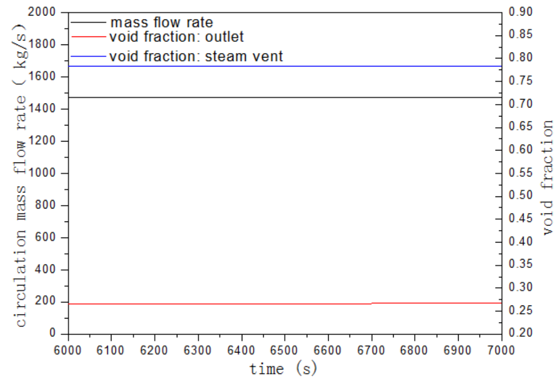
(a)Inlet subcooling:19℃



(b) Inlet subcooling:17℃



(c) Inlet subcooling:4℃

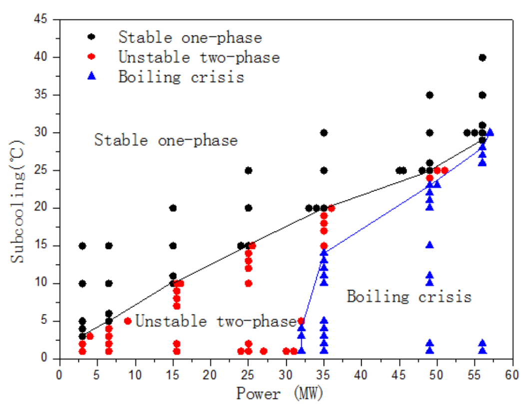


(d) Inlet subcooling:1℃

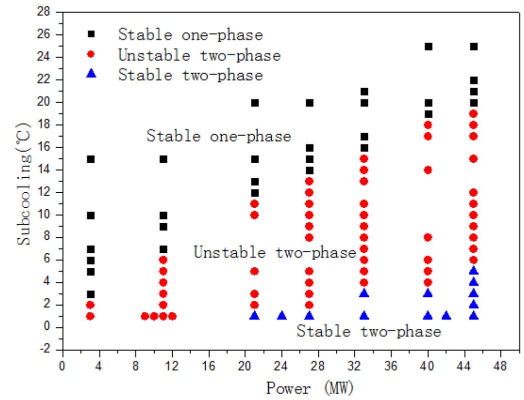
Fig. 3 Representative waveforms at 2.5 bar and 40 MW

3.2. Effect of system pressure, power, and inlet subcooling

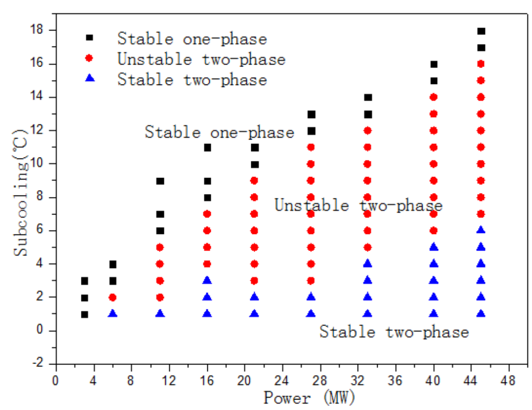
Several results have been carried out to derive so-called stability maps. These maps are represented in the power-subcooling plane in the present discussion. Stability maps have been constructed at a pressure of 1 bar, 2.5 bar and 4.0 bar. The results are shown in Fig. 4. Fig. 5 gives the stability boundaries at system pressures of 1 bar, 2.5 bar, and 4.0 bar, obtained from Fig. 4. The range of inlet subcooling for which instabilities occur increases with power and decreases with pressure. Increasing system pressure has a stabilizing effect also because it reduces the relative amplitude of flow oscillations. However, the boiling crisis can occur at outer surface of the lower plenum vessel as the power increases when the system pressure is 1bar.



(a) System pressure=1 bar



(b) System pressure=2.5 bar



(c) System pressure=4.0 bar

Fig. 4 Stability maps in reference to power and inlet subcooling

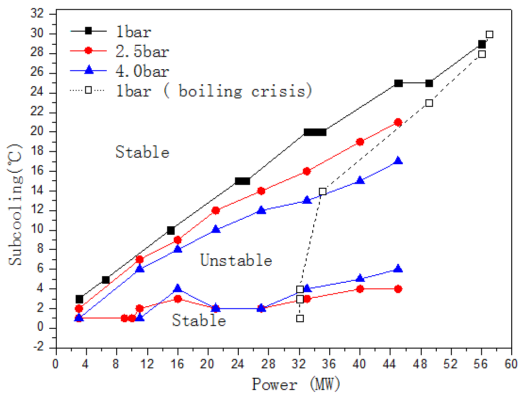


Fig. 5 Stability map at System pressure = 1 bar, 2.5 bar, and 4.0 bar.

The above analyses were performed under the conditions of which kept the parameters constant except the one whose effect on stability would be studies. However, it is hard to compare the stability performance in these planes, since if the operational conditions are varied, the mass flow rate will also change. So non-dimensional parameters are used to analyze the influence effects of parameters. The stability maps can be shown by these non-dimensional parameters. Such a result is given in Fig.6.

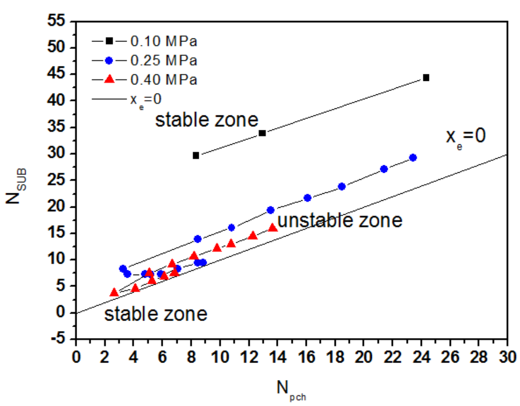


Fig. 6 Stability map at System pressure = 1 bar, 2.5 bar, and 4.0 bar using non-dimensional parameters.

The figure shows that N_{sub} will increase with an increase of N_{pch}. The flow instability is Type-I instabilities because the results of the calculations were located the region of low equilibrium quality as shown in Fig. 6.

3.3. Effect of inlet restriction on instability

Fig. 7 gives the stability boundaries map at system pressure of 2.5 bar, and inlet restriction K_{in}=43. By increasing the inlet restriction coefficient the system becomes more unstable since the unstable area slightly enlarges. From the figure it is clear that the stable two-phase area slightly enlarges too.

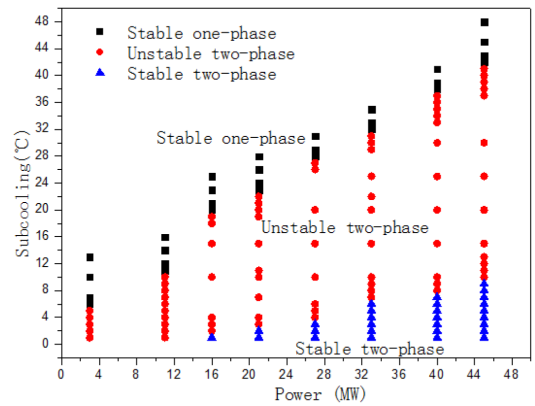


Fig. 7 Stability map when K_{in}=43

CONCLUSIONS

Flow instability is quite an important phenomenon in natural circulation and it can be classified into two types. The Type-I is simulated using RELAP5 in this paper.

An unstable region exists between stable single-phase and two-phase circulation. Flashing is the main contributor to these instabilities. Stability maps were obtained in terms of the inlet subcooling and the power for various system pressures. The maps for Type-I flow instability in the plane of N_{sub} and N_{pch} were also obtained. It can be seen that the system become more stable with an increasing pressure. Increasing the inlet restriction coefficient the system becomes more unstable.

NOMENCLATURE

h	specific enthalpy(kJ kg^{-1})
v	specific volume(m^3 kg^{-1})
Q	heated power(W)

W mass flow rate(kg s^{-1})

Subscripts and superscripts

fg difference between (saturated)vapor and liquid properties

in inlet

f fluid

Abbreviations

IVR in-vessel retention

ERVC external reactor vessel cooling

PWR pressurized water reactor

TDV time dependent volume

P pipe

SJ single junction

B branch

Non-dimensional numbers

N_{sub} subcooling number:

$$N_{sub} = \frac{v_{fg}}{v_f h_{fg}}(h_f - h_{in})$$

N_{pch} phase change number:

$$N_{pch} = \frac{v_{fg}}{v_f h_{fg}}\frac{Q}{W}$$

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